9-fold Fresnel–Köhler concentrator with Fresnel lens of variable focal point

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Abstract: Non-uniform irradiance patterns over Multi-Junction Cells gives rise to power losses, especially when considering spectral irradiance distributions over different junctions. Thermal effects on Silicone-on-Glass lenses affect spectral irradiance distributions. A new Photovoltaic Concentrator (CPV), formed by nine optical channels, each one with a Köhler configuration, has been designed to overcome these effects at high concentrations for a large acceptance angle. A Fresnel Lens with a Variable Focal Point is proposed to prevent optical crosstalk in multichannel systems. When integrated into the concentrator, improves the acceptance angle. These designs are designed to fulfill the expected requirements of four junction CPV systems.

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1. Introduction

Concentrator Photovoltaic (CPV) systems, to minimize cost of electricity (€/kWh), have to achieve several goals. The currently commercialized triple-junction solar cells take advantage of the high efficiency through partioning of the solar spectrum. To be cost effective, systems with these cells require high concentration (above 500X) and high acceptance angle. The acceptance angle provides tolerance against tracking misalignments and manufacturing errors, and has a tradeoff with the concentration. This tradeoff is described through the concentration-acceptance angle product *CAP*, defined by

$$CAP = \sqrt{C_g}\sin\alpha \tag{1}$$

where C_g is the geometrical concentration and α the acceptance angle, defined as the incidence angle at which the power collected by the system decreases to 90%. *CAP* is remarkably constant for the same concentrator design for different concentrations, being an appropriate merit function for a concentrator [1]. Additionally, thermodynamics establishes upper bound on any *CAP*: $CAP < n$, when n is the refractive index of the dielectric material surrounding the receiver.

MJ cells typically consist of a monolithic arrangement of several small sized photovoltaic cells, series connected to decrease power losses caused by series resistance. The series interconnection has the effect that the subcell which is exposed to the least irradiation limits the photocurrent of the whole cell. Due to this fact, a spectrally balance flux over the entire cell is required to avoid power losses. In the case of the spectral bands of the different junctions are not matched for all points of the cell, internal currents spreading perpendicular to the main current flow must appear to balance the local photocurrent mismatch[2]. Additionally, the irradiance must be uniformly spread to decrease the lateral cell resistance. However, the typical irradiance patterns created by conventional CPV concentrators are considerably spatial and spectrally non-uniform, and power losses can be significant. Although the exact value is difficult to determine to a number of variables, simulations with ray-tracing and 3D distributed models of MJ cells indicate that the efficiency can drop up to 2% due to non-uniformity flux caused by typical CPV systems[3][4]. The uniform irradiance distribution has to be achieved for the entire spectrum for which MJ cells traps photons, because the photocurrent has to match between different junctions. In fact, when chromatic aberrations between irradiance distributions over the different junctions are significant, the effect on power losses increases considerably [3--5].

Recent advances in 4 and 5 junction solar cells suggests that the spectrum balance and irradiance uniformity between different junctions will be increasingly important for future CPV systems [6]. Recently, Soitec announced a four-junction solar cell with 44.7% [7], which is a very promising result, especially when considering the learning curve which this technology still has to accomplish. In the near future, these cells are expected to reach efficiencies of more than 50%. These cells are likely to be more expensive, and there is a strong possibility that higher levels concentrations will be needed to be cost effective (although the increase of efficiency can level it up).

The progress in the development of advanced CPV optical designs has proven that spectral balanced high irradiance uniformity, while maintaining a high acceptance angle is achievable, for concentrations of 850-1000x. This technology is known as Fresnel-Köhler [8--9]. This technology is based on Köhler integration, using a Fresnel lens as Primary Optical Element (POE). The fundamentals of the general design procedure are described in [10]. The main idea is to concentrate the sunlight through Köhler integrator pairs divided in four channels, each one comprising two optical surfaces, an already mentioned Fresnel lens as POE, and a free-form surface in the Secondary Optical Element (SOE). The degrees of freedom of using free-form surfaces allow the introduction of multiple functionalities in the optical surfaces. Specifically, these provide a high *CAP* with excellent light homogenization for any sun position within the acceptance angle. Regardless of the complexity of optical designs, the free-form elements can be manufactured using the same techniques as classical design optics (glass modeling, plastic injection molding, embossing and casting), thus the production cost does not increase. In this paper, Fresnel-Köhler concentrator of four sectors will be referred as FK4.

As mentioned, FK4 accomplishes the purpose of high acceptance angle and high irradiance uniformity, for concentrations of 850-1000x, which has been the typical concentration values used for CPV systems of three Junction cells. However, when aiming for a larger concentration, spectral irradiance uniformity decreases for Fresnel-Köhler architecture, as well as the acceptance angle, as previously mentioned. Irradiance uniformity deterioration with concentration has been demonstrated in [5] (for a SILO system, which has almost perfect uniformity at 300x [11]). This deterioration maybe debatable for other concentrators. In ideal concentrators, every point of the cell is isotropically illuminated by rays coming from the concentrator aperture within the acceptance angle. In this case and when the acceptance angle equals the Sun's angular diameter, then the irradiance on the cell must be uniform. This case is not very common because the concentrator manufacturability tolerances require an optical design with an acceptance angle noticeable greater than the Sun's angular size, to have a proper energy collection. FK concentrator, although not ideal, may behave like this for very narrow acceptance angles, near the Sun's angular size.

Interest on Silicone-on-Glass (SoG) lens for CPV applications has been growing due to combining mass production simplicity and high resistance to external factors, and several companies have adopted this technology [12--14]. SoG lens are especially suitable when CPV systems are installed in aggressive environments as sand deserts (typically with high DNI), as glass resistance to scratches is significant higher than PMMA's. However, SoG lens are quite sensitive to thermal effects, not only due to mechanical contractions, but also due to variations in the refractive index. These effects have been well documented [15--17]. In this work show that this variation has a considerable influence on spectral balance of irradiance distributions.

This paper proposes a new CPV optical design. Based on the arrays of Köhler integrators,

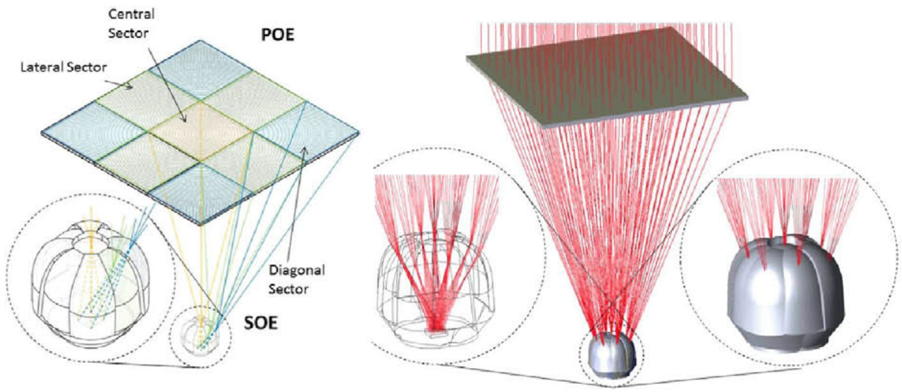

Fig. 1. *On the left* - Schematic view of FK9 concentrator. Three different fold types, central, lateral and diagonal (in the picture, orange , green and blue, respectively) form a 9 fold system. Each sector of the SOE images the corresponding sector of the POE in the cell. *On the right* - FK9 ray tracing simulation, where the 9 focus on SOE sectors are visible, as well as the image on the cell.

the concept is further extended to a larger number of channels. 9-fold Fresnel-Köhler (FK9) concentrator design is presented, and realistic simulations results are shown. This work shows that FK9 design is prepared to work at very high concentration levels (up to 2000x), maintaining a high irradiance uniformity for the desired spectral range. When the number of channels increases, the possibility that light crosstalk between different channels also increases, thus decreasing the acceptance angle. In this work we explore a new technical solution to overcome the crosstalk issue, and a Fresnel Lens with Variable Focal Point (FL-VFP) is proposed, which avoids that light impinging in extreme points of the POE crosstalk to other channels of the system. It is shown that this novelty further enhances the acceptance angle.

FK9 is designed to satisfy the expected requirements of 4 and 5 junction based CPV systems.

2. Technical description of FK9

FK9 consists on a Primary Optical Element (POE), a flat Fresnel lens divided in 9 sectors, and a Secondary Optical Element (SOE) also divided in 9 sectors, all of them free form, and coupled with the respective sector of the POE, as seen in Fig. 1. The POE consists in 1 symmetric central sub Fresnel lens, four lateral and for diagonal sub Fresnel lenses, each of them symmetric with each other relative to the Fresnel lens center. Each one of the four lateral and four diagonal sub-lenses may be seen as off-center square pieces of a symmetric Fresnel lens, each one with their one axis of symmetry.

The SOE has the same structure: 1 central sub-lens, four lateral and four diagonal sub-lenses, all symmetric with each other relative to the center axis, all of them free form. Each sub-lens is coupled with a sector of the POE, imaging each square sector of the Fresnel lens into the cell, thus performing Köhler integration. This integration allows that, even when the concentrator is misaligned with an angle within the acceptance, each surface of the SOE can still control the incoming bundle from each sector of the POE and redirecting into the entire cell surface, allowing an excellent irradiance uniformity, even for off-axis angles. The fact that the input bundle is divided into 9 different bundles enables a smaller beam angle of each bundle coming from the different sectors of the SOE. Also, allows that the thermal stress of each light spot inside the SOE is reduced by the ninth. The optical design is optimized such that the extreme rays that impinge in the POE are directed into the extremity of the cells, both for an aligned angle as for a design acceptance angle.

The integration allows for an excellent spectrum and spatial irradiance on the cell, even at very high concentrations and extreme thermic conditions, as presented below. The fact that the incoming bundle of Sun rays is divided into nine channels makes that each SOE sector will need to manage a correspondingly smaller field of view and also provide a smaller magnification. This eases the goal to obtain a very high acceptance for rays coming from any direction, thus allowing a high *CAP*. Moreover, this incoming light split reduces the risk of glass solarization in the SOE if compared with other conventional Fresnel-based concentrators, where a single light focus appears inside the SOE.

FK9 optical surfaces are very similar to those in other conventional concentrators, from a manufacture point of view. The POE of the FK9 is similar to conventional flat Fresnel lenses, while the SOE is equivalent to typical dome-shaped SOEs used in other concentrators. This implies that the same low-cost and already mature manufacturing techniques, such as compression molding, hot embossing and glass molding, can be applied to this concentrator, thus the production cost is approximately the same as for these methods. Although the fabrication of the mold of the POE is more demanding than a conventional Fresnel lens due to segmentation and assembly, for volume manufacturing the potential for cost reduction is increased due to loose assembly/alignment tolerances (through high acceptance angle) [18].

3. Fresnel Lens with Variable Focal Point

Multichannels systems design always have to struggle with optical crosstalk between different channels. For solar concentrators, where it is intended the acceptance cone to be as large as possible for each channel, it can result in a major issue, which limits the *CAP* of the system.

In FK9, although the concentrator has already a high *CAP* (as presented in Section 4), the major limitation to further increase this quantity is the crosstalk between different channels

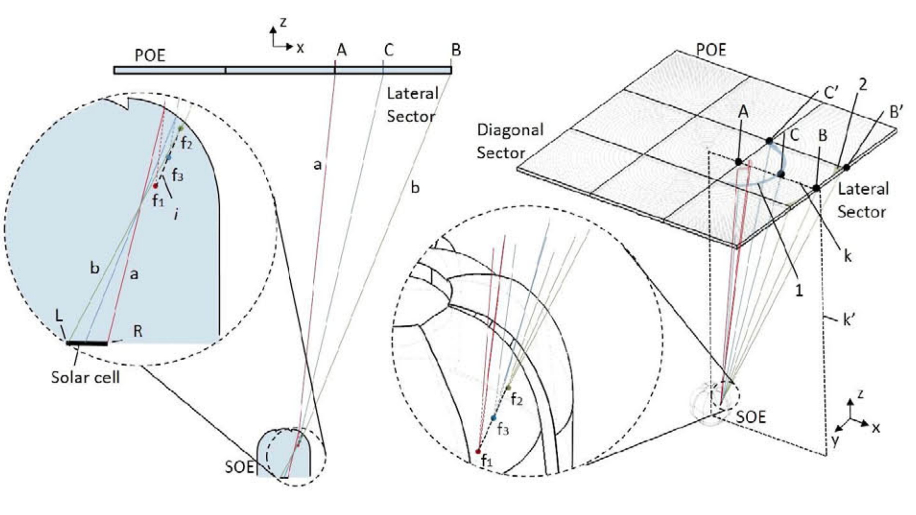

Fig. 2. Schematic view of FK9 with Fresnel Lens with Variable Focal Point (FL-VFP). *On the left* - Section view of the concentrator on the optical axis plane. *On the right* - Isometric schematic view of the system.

that occurs when the system is at a considerable off-axis angle. Crosstalk happens between sublenses of the SOE, especially for rays that are refracted in areas of the Fresnel lens which are farther away from the optical axis. The main limiting errors for this situation are the chromatic aberrations of Fresnel lens. In this section, a Fresnel lens with variable focal point is proposed, which has the ability to control the rays coming from extreme points, i.e., apart from the optical axis.

Consider Fig. 2, where both problem and the proposed solution are explained. In this case, only the Fresnel lens of the lateral sector of FK9 is considered, although the same considerations can be made to the diagonal sector. To fulfil the requirement that the whole cell area is uniformly illuminated, Köhler integration has to be achieved, and ray *a* and *b*, coming from the optical axis boundaries of the Fresnel lens in an on-axis case, have to impinge on the extremes of the solar cell *R* and *L*. While the first condition is ensured by the free-form surface of the SOE and direction of ray *b*, for the second one, it is required that the "virtual" focal point of the Fresnel lens is in position f_1 (virtual because the focal point actually does not exist, due to the refraction of rays in the SOE surface). The fact that the focal point is at a considerable distance from the surface of the SOE makes that, for an off-axis angle, rays refracted in points far from the optical axis *k* such as points *B'* and *C'* will refract in SOE in points far from the optical axis vertical plane *k'* in the *y* direction. This implies that, from a specific off-axis angle, these rays will crosstalk with the facet of the SOE's diagonal sector. The same crosstalk situation occurs for the diagonal sector.

The proposed solution to avoid optical crosstalk and further enhance the concentrator performance is a **Fresnel Lens with Variable Focal Point (FL-VFP)**. FL-VFP intents to add an extra degree of freedom to the Fresnel lens, such that rays refracted in points distant from the optical axis can be further controlled, without perturbing the Fresnel rotational symmetry and maintaining Köhler integration. Once again, consider Fig. 2. In FL-VFP, while you move farther away from point *A* to point B in the *x* direction, the focal point of the corresponding Fresnel lens tooth changes along line *i* from f_1 to f_3, always on the optical axis plane *k'*. This arrangement allows that tooth *1* (and its corresponding points *C* and extreme point *C'*) and tooth *2* (and its corresponding point *B* and extreme points *B'*) focus in points f_2 and f_3, respectively. Therefore, rays coming from points in POE far from the optical axis *k* have a focal point *closer* to the SOE's surface, and will refract on the SOE *closer* to symmetry plane *k'*. Consequently, the

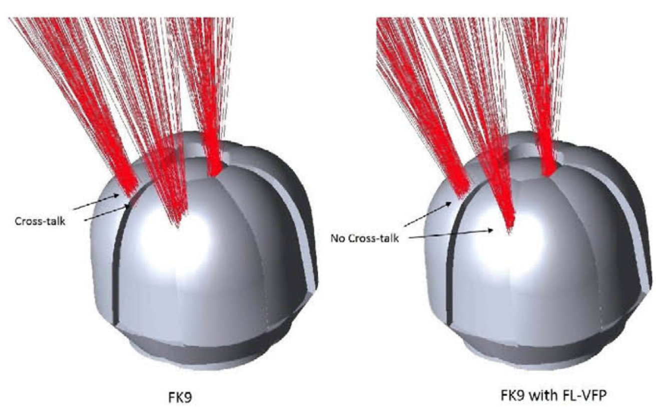

Fig. 3. Ray tracing of 1000x FK9 and FK9 with FL-VFP for an off-axis angle of 1.2°. On the left, it is visible the optical crosstalk situation on the SOE while on the right, with FK9 with FL-VFP, the crosstalk is prevented, further improving the acceptance angle.

off-axis angle to which crosstalk is avoided further increases, increasing the acceptance angle of the system.

To ensure that point f_3, focal point of tooth *1* is close enough to the surface, the function *r* that relates the distance *t*, the distance between a generic tooth *4* and point *A* and the distance *i*, distance between f_1 and f_4, focal point of tooth *4*, is an hyperbolic function, due to its rapid growth.

Fig. 3 shows the positive effect of FL-VFP. For an off-axis situation of 1.2°, it is noticeable the capability of FL-VFP to prevent an optical crosstalk situation for an 1000x FK9.

4. Simulation results for $C_g = 1000x$

Simulation results are presented for both FK9 and FK9 with FL-VFP, designed for a geometrical concentration of **C_g = 1000x** (over cell illuminated area) and a **F-number of 1**. All the following simulation results correspond to raytracing simulations carried out under the same realistic conditions: AM1.5D sunlight spectrum, finite sun (±0.265°) and Fresnel and absorption losses. POE is made on PMMA, and SOE is made on Schott B270 glass. Moreover, no anti reflecting coating has been applied on SOE. POE teeth rounded edges were not considered.

Figure 1 presents a ray tracing simulation of FK9 concentrator. The optical behaviour at normal incidence of the system can be observed: each focus of the nine POE sectors impinging in the correspondent SOE sector surface are integrated, and equally distributed over the entire cell surface.

Table 1 summarizes the main results of both FK9 and FK9 with FL-VFP optical performances, and Fig. 4 presents their acceptance curves.

1000x FK9 has an acceptance angle of ±1.12°. Also, the curve almost maintains its maximum efficiency until it reaches 1° of deviation, ensuring a very high efficiency within the

Table 1. FK9 and FK9 FL-VFP concentrator simulation results for C_g=1000x.

C_g=1000x	FK9	FK9 FL-VFP
Optical Efficiency	83.9%	83.8%
Acceptance angle	±1.12°	±1.2°
CAP	0.62	0.66
f-number	1	

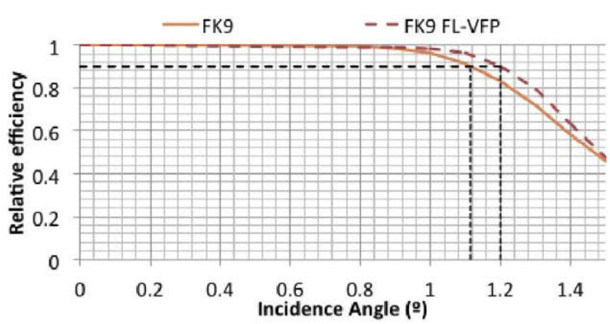

Fig. 4. FK9 and FK9 FL-VFP acceptance curves for $C_g = 1000x$. For the FK9, acceptance angle is ±1.12°, while for FK9 with FL-VFP, the acceptance angle is ±1.2°.

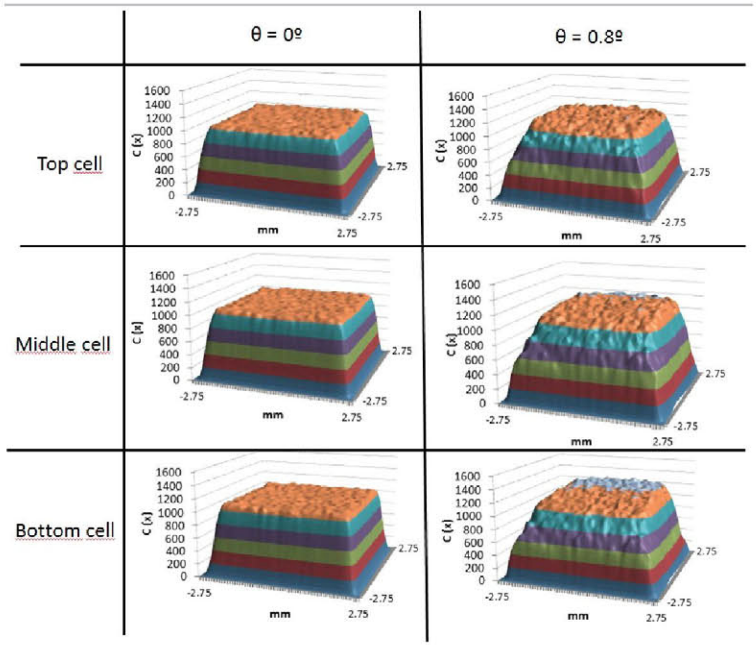

Fig. 5. 1000x FK9 spectral irradiance distributions for Top, Middle, and Bottom junction of a Triple MJ cell, for normal incidence and for a misalignment angle of 0.8°. The irradiance distribution is analyzed throughout the full Sun light spectrum.

acceptance angle. The concentration level of $C_g = 1000x$ and an acceptance angle of $\pm 1.12^\circ$ represents a CAP of 0.62, a considerable improvement due to a higher number of channels. The losses that can be observed after 1° of deviation are mostly due to Fresnel reflection effects on the SOE surface. This implies that, if an optimized anti reflecting coating for the appropriated incidence angles is applied on the SOE optical surface, the acceptance angle and the CAP can be further increased, Moreover, a global efficiency increase of 2% can be expected if a proper anti reflecting coating is applied.

When the Fresnel Lens with Variable Focal Point (FL-VFP) is introduced in FK9 design, although the complexity of the system increases, it has the advantage that the acceptance angle rises to $\pm 1.2^\circ$, which represents a *CAP* of 0.66. This considerable increase is due to the fact that FL-VFP can prevent optical crosstalk for a higher off-axis angle.

Figure 5 represents the spectral irradiance distributions on each junction of a triple MJ cell that FK9 produces. FL-VFP does not affect the irradiance distributions, and the results with it are the same. Spatial irradiance is presented for two different incidence angles, at normal incidence and with a misalignment of 0.8°, within the acceptance angle. At normal incidence, spatial irradiance is almost perfectly uniform for all junctions. This uniform spatial irradiance is kept for the full Sun light spectrum. This is especially important to avoid current mismatches between junctions and high series resistant losses, and even more if one considers cells with 4 and 5 junctions, as they are more likely to be sensitive to spectrum variations, thus it is more difficult to achieve current mismatch.

For a misalignment of 0.8°, the spatial irradiance is still very uniform, especially in the Top and Middle junctions. When dealing with the widely used Ge-bottom MJ cells, the current is

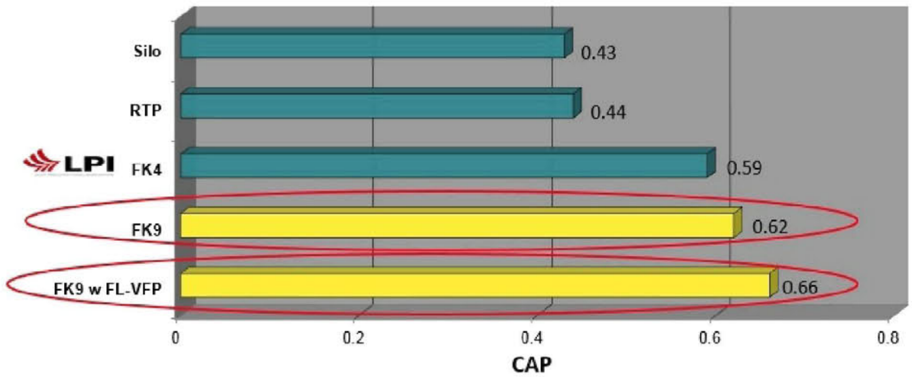

Fig. 6. Comparison of CAP between different Fresnel lens-based systems with rather good to excellent irradiance uniformity.

typically limited by the Top and Middle junction, thus is likely that this less uniform distribution on the Bottom Cell does not have a considerable effect on the overall performance. Köhler integration on every surface of the SOE enables that the spectral irradiance is essentially constant within the acceptance angle.

Figure 6 presents a *CAP* comparison between different systems, in which all of them were designed for achieving the most uniform spatial and spectral irradiance possible through Köhler integration. While FK4 and FK9 are the systems with highest performance in this field, FK9 still outperforms the FK4 concentrator, presenting a higher *CAP* of **0.62** and higher acceptance angle, therefore reaching a higher tolerance value. Using FK9 design with the FL-VFP, this value further increases to **0.66**, being the highest value amongst the Fresnel-based systems designed for excellent irradiance uniformity.

5. Spectral irradiance distributions at high concentrations and high temperatures

To analyze the effects of high concentrations and thermal variations in SoG lens based CPV systems on the spectrum irradiance distributions, a comparative study between three different SoG lens-based systems was made to evaluate their irradiance and spectral maps when designed for 1000x and 2000x concentration ratio, at two different POE temperatures, 20°C and 45°C. The analyzed systems were the Silo, FK4 and FK9 (Fig. 7). These systems were chosen for their capability of creating uniform spectral irradiance distributions at a specific concentration level. All three systems were designed with a SoG lens as POE, and an SOE made of b270 glass. The systems were designed for a POE temperature of 20°C.

According to some previous works [15--17], the variation of index of refraction affects only the focal distance of the lenses, while the thermal expansion of the lens facets produces a widening of the flux profile. Due to the design procedure of FK, the latter affects mostly the acceptance of the system, while the change of the focal distance affects the spectral irradiance. In this work, only this effect is studied, so no thermal expansion was taken into account. The index of refraction dependence with temperature of SoG lenses was defined according to [17]. For a difference of 25°C, a decrease of -0.009 is considered for SoG lens refractive index. Only Bottom and Top cell irradiance distributions are presented to represent the most extreme cases.

All results are presented in Fig. 7. It can be seen, that for 1000x at $T_{POE} = 20°C$, the SILO already presents a non-uniform irradiance, especially at top cell. For this same concentration, when T_{POE} increases to 45°C, the refractive index variation causes a considerable change in bottom cell irradiance distribution. Considering C_g=2000X, this effect is even clearer: for $T_{POE} = 20°C$, the non-uniformity has increased considerably in both junctions, only due to the concentration increase. If we analyze an even more extreme case of C_g = 2000x and $T_{POE} = 45°C$, the non uniformity in bottom cell irradiance has a dramatic change.

FK4 and FK9, as expected and presented previously, have an excellent spectral irradiance distribution for both cells, at 1000x and $T_{POE} = 20°C$. When temperature increases to 45°C, FK4 bottom cell irradiance uniformity suffers a slight decrease, while the FK9 maintains the irradiance uniformity in both junctions. Still, these results are also supported by previous work [19], where is showed that FK4 has a high tolerance to color separation for a vertical misalignment of the SOE.

When C_g = 2000x is considered, while both FK4 and FK9 still maintain an almost excellent uniformity for both junction at $T_{POE} = 20°C$, for $T_{POE} = 45°C$, FK4 suffers a significant non uniform variation for the Bottom cell irradiance, while FK9 uniformity variation in both junctions is almost negligible, maintaining an excellent uniformity.

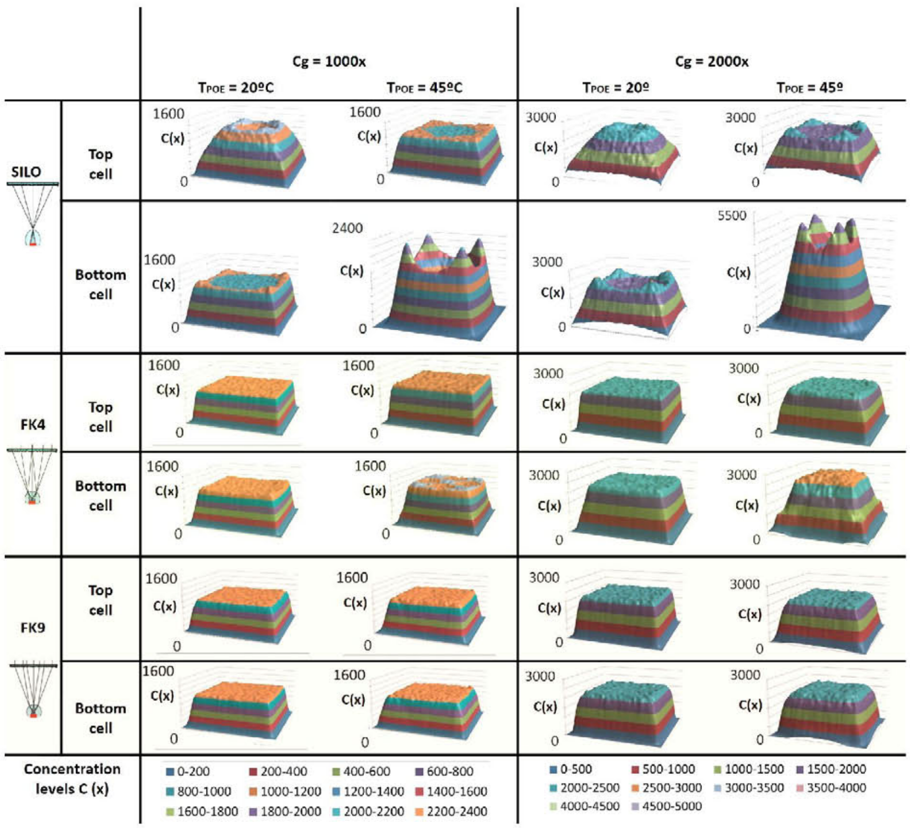

Fig. 7. Spectral Irradiance distributions on Top and Bottom cell for three different CPV systems well known for their excellent irradiance uniformity at specific concentrations - *C(x) gives the irradiance on the point x over the irradiance at the concentrator's aperture (Fresnel lens).*

6. Conclusion

CPV systems still have to strive to reach a Levelized Cost of Electricity able to compete with other energy sources. To accomplish it, it is essential to decrease the production cost and increase the energy collection and power production. The recent advances in 4 junction cells are a promising start to reach a higher power production, and 9-fold Fresnel-Köhler concentrator (FK9) is an excellent candidate for 4 junction-based systems, due to its high acceptance angle and excellent spatial and spectral irradiance distribution.

FK9, using conventional Fresnel lenses, presents an excellent spatial and spectrum irradiance distribution for each junction of a Triple MJ cell and has a *CAP* of 0.62, with $\pm 1.12°$ for $C_g = 1000x$, being the highest among the normal Fresnel lens based system up to the date.

In this paper, a Fresnel Lens with Variable Focal Point (FL-VFP) is also proposed, to prevent optical crosstalk between channels for a higher off-axis angle. when FL-VFP is integrated in FK9, CAP increases to 0.66 ($\pm 1.2°$ for $C_g = 1000x$), maintaining the uniformity in spatial and spectral distribution.

The irradiance distribution on the different junctions of a Triple MJ cell is excellent for normal incidence, and is essentially constant within the acceptance angle, enabling that no losses due to current mismatches occur, even for misaligned angles.

A comparative study showed not only that high concentration levels and high temperatures (on SoG lens based systems) affect significantly the spectral irradiance distributions, but also that the design of FK9 is prepared to overcome these aberration effects, maintaining an excellent uniformity for all junctions even in extreme conditions.

This capability is important for 4 and 5 junction cells, due to the fact that these cells are likely to require high spectral irradiance uniformity and high concentration for an efficient and cost effective system.

FK9 is designed to fulfill the expected requirements of 4 and 5 junction based CPV systems.

Acknowledgments

The FK-9 is proprietary technology of LPI-LLC with US patent 8,000,018 and international patents pending, WO2010059657(A3), WO 2013158634 A1. Authors thank the European Commission (SMETHODS: FP7-ICT-2009-7 Grant Agreement No. 288526, NGCPV: FP7-ENERGY.2011.1.1 Grant Agreement No. 283798), the Spanish Ministries (ENGINEERING METAMATERIALS: CSD2008- 00066, SEM: TSI-020302-2010-65 SUPERRESOLUCION: TEC2011-24019, SIGMAMODULOS: IPT-2011-1441-920000, PMEL: IPT-2011-1212-920000), and UPM (Q090935C59) for the support given to the research activity of the UPM-Optics Engineering Group, making the present work possible.

This work was partly supported by Fundação para a Ciência e Tecnologia, Scholarship SFRH / BD / 80892 / 2011.